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Strategic Weapons Assessment Nomograph
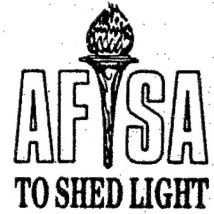
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STUDY DIRECTOR:
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FOREWORD

The Assistant Chief of Staff Studies and Analyses requested an investigation into the interrelationships between the various strategic weapon characteristics. The intent of this investigation was to develop a graphic model that could show all of these relationships on a single chart, thereby facilitating quick, desk top evaluations of strategic weapons in order to provide insights into a weapon's overall capabilities. Members of the Forces Division, Directorate for Strategic Force Analyses, Air Force Center of Studies and Analyses conducted this investigation.

The resultant model, called the Strategic Weapons Assessment Nomograph, has thus far been presented to the Air Staff Board and the Strategic Offense Panel, with numerous other agencies and organizations projected for the coming year, including the Military Operations Research Society. Widespread dissemination of this model among analysts and decision makers alike is also anticipated.

Captain Douglas W. Owens was the lead on this study, with study guidance and analytical support from Col Anthony L. St Amant, Col Terrence L. Dillon (ret), Lt Col Philip E. Nielsen, Maj Raymond B. Yoh, Maj William D. Davis, and Capt Judith A. Gamble. Mr George Berard and Mr Robert June provided graphics support.

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This study investigates the interrelationships among the various strategic weapon characteristics by developing a graphic model showing these relationships on a single chart. The Strategic Weapons Assessment Nomograph (SWAN) model interrelates the following key parameters: circular error probable (CEP), yield, target hardness, pre-launch survivability, weapon system reliability, and probability to penetrate. Each parameter appears separately on the nomograph, yet all are interrelated through a fixed mapping structure. The SWAN can be used by analysts and decisionmakers in guiding detailed studies of strategic weapons and in performing quick assessments of tradeoffs among weapon systems and their individual characteristics. The SWAN is best suited for single-weapon-on-single-target type analysis but can also be used for broader and more detailed studies. Presenting all of these strategic weapon parameters simultaneously in a single graphic model provides insights into weapon capabilities and reveals numerous potential applications.

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83 APR edition may be used until exhausted.
All other editions are obsolete.

TABLE OF CONTENTS

LIST OF FIGURES

The Strategic Weapons Assessment Nomograph

In the myriad of strategic weapons characteristics, it is difficult to identify, let alone interpret, the interrelationships among these characteristics. Such parameters as yield, circular error probable, probability to penetrate, target hardness, and so forth can be analyzed independently through any number of models. However, it is difficult to assess the overall capabilities of weapons without looking at all their characteristics simultaneously. Furthermore, reliance on detailed models hinders analysts as well as decisionmakers from performing quick tradeoffs between the various weapons characteristics in order to better determine the direction, if any, of indepth analyses. Developing a graphic model that shows all of these relationships could provide helpful insights into a weapon's overall capabilities, offering guidance in studies and decisions.

The Strategic Weapons Assessment Nomograph (SWAN) is a graphic portrayal of the relationships among the various parameters used in calculating damage expectancy (DE). It is intended for use by analysts and decisionmakers in guiding detailed studies of strategic weapons and in performing quick-reference assessments of weapon systems. One not only can obtain "ballpark" values for probability of damage (PD) and damage expectancy (DE), but also, and perhaps more importantly, can easily see the overall relationships among the numerous parameters. Seeing "the big picture" offers various insights into strategic weaponry and targeting issues and their impacts on force modernization decisions.

This tutorial describes the model and its utility, beginning with a quick summary of the mathematical procedures used in calculating DE and the assumptions and constraints applied in building this model. With this understanding of where the numbers came from, I will then present the graphic DE model, how to use it, and how to address some of the model's limitations. This will be followed by a discussion of some insights into the model and what this graphic view reveals. As a follow-on to this tutorial, a classified appendix under separate cover presents some potential applications for the model.

1.   CALCULATING DAMAGE EXPECTANCY

There are numerous sources of information that describe the mathematical procedures for calculating damage expectancy (DE). Therefore, I will not attempt to aggregate all such sources, rather, I will briefly describe the functions involved and some of the key assumptions I have made in developing the Strategic Weapons Assessment Nomograph. For further explanation, see such works as "How To Calculate Probability of Destruction (PD) and Damage Expectancy (DE)" by SAIC (Science Applications, Incorporated) and AP-550-1-2-INT "Physical Vulnerability Handbook - Nuclear Weapons" by DIA.

The DE Function

Damage expectancy (DE) is the probability of inflicting a specified level of damage on a target. DE is expressed as the probability of damage (PD) multiplied by the probability of arrival of the weapon (PA):

$$DE = PD \times PA. \tag{1}$$

Only probabilities for a single weapon aimed directly at a single target are used here. Consequently this rules out any strong applicability to offset targeting since the SWAN assumes a zero offset distance. (Offset distance is the lateral distance from the ground zero point to the targeted installation. This is the desired distance away from the installation at which the weapon should detonate; commonly used in attacking multiple soft targets with a single weapon.)

The PD Function

Probability of damage (PD) is the probability of inflicting a specified level of damage on the target, given that the weapon arrives and detonates in the target area. Under the zero offset assumption, PD is a function of the circular error probable (CEP) of the weapon, the yield of the weapon, the hardness of the target, and the height of burst. These terms are defined as follows:

CEP (circular error probable) - - the radius of a circle about the desired ground zero detonation point within which 50% of the weapon's projectiles are expected to fall.

Yield - - the energy release of the weapon expressed in tons of TNT.

Hardness - - the blast strength of the target expressed in pounds per square inch (psi) of static overpressure, indicating the pressure needed to cause a specified level of destructive damage on a target.

HOB (height of burst) - - the distance above the ground zero point of the target at which the weapon should detonate. The optimal HOB is that height at which the maximum probability of damage (PD) occurs for a particular yield and target hardness.

The mathematical equations that interrelate these parameters appear at the beginning of Appendix I. In calculating PD for building the SWAN, the optimal height of burst is used in all cases. Furthermore, the target hardnesses are expressed in equivalent psi of static overpressure. These psi levels are determined through the VNTK system, which is an alphanumeric representation of a target's susceptibility to blast effects. Characteristics of both the target and the weapon are taken into account in assigning values to define a specific target. (Appendix I offers a detailed discussion on VNTK and how it was used in

2

constructing the SWAN.) Within this system, it is assumed that static overpressure is the only damaging mechanism acting on the target. Furthermore, no adjustment is initially made for varying effects of different yields, thereby assuming the target is insensitive to the pulse duration of the overpressure (i.e., the K-factor in the VNTK system is zero). Section 3 addresses this constraint more fully and presents a variation of the original model. In either case, each hardness curve on the SWAN represents an equivalent psi level, converted to pure static overpressure.

The PA Function

The probability of arrival (PA) is the probability that the weapon will arrive and detonate in the target area. PA is a multiplicative function of the probability of pre-launch survival (PLS), the weapon system reliability (WSR), and the probability to penetrate (PTP):

$$PA = PLS \times WSR \times PTP \qquad (2)$$

To appreciate the subjective complexity of assessing each of these parameters, some of the key factors/issues are listed here:

PLS - - based on expected warning times, promptness of response to launch orders, and the force generation state.

WSR - - based on maintenance factors such as mean time between failure and mean time to repair, operational performance records, and operational test and evaluation results.

PTP - - based on the defensive capabilities and maneuverability of the overall weapon system (e.g., ECM, terrain following radar) and the expected area defense capabilities of the target area.

Sometimes PA also includes a C3 factor that indicates the probability that the weapon system receives the execution order:

$$PA = PLS \times WSR \times PTP \times C3 \qquad (3)$$

However for the purposes of this tutorial, C3 is assumed to be 1.

2. MODEL DESCRIPTION

After investigating the relationships among these numerous parameters, graphic representations of each were plotted. Figure 1 is the Strategic Weapons Assessment Nomograph constructed from the concepts previously discussed. For further details, Appendix I discusses how each part of the model was obtained.
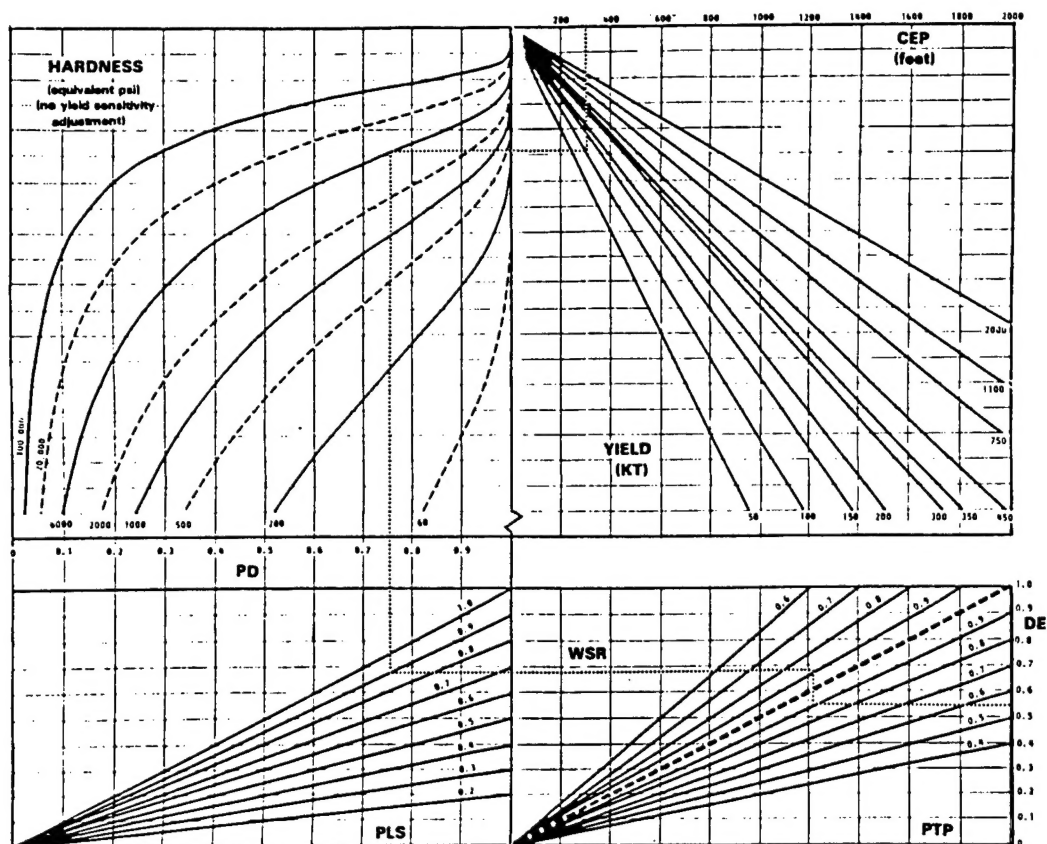
Figure 1. The Strategic Weapons Assessment Nomograph

How To Use The Model

Each of the DE parameters is tied together through a fixed structure. In essence, it's a type of circular mapping structure. To best understand this, let's trace through an example. Consider the following weapon system and target parameters:

CEP	300 feet
Yield	100 KT
Hardness	6000 psi
PLS	0.9
WSR	0.9
PTP	0.9

Tracing through Figure 1, we enter on the CEP scale at 300 feet. We now move down to the 100 KT line. At this point of intersection, we then move left to the hardness chart until we reach the 6000 psi line. Now we move down to the PLS chart until we intersect the 0.9 line. (Note that we crossed the PD scale at about 0.77, the probability of damage based on a 300 feet CEP, a 100 KT yield, and a 6000 psi target.) From the PLS chart, we move right to the WSR chart, stopping at the 0.9 line. Next we move down to the 0.9 PTP line. Finally we move right to the DE scale where we read a 0.56 DE.

The path followed in this example is just one possible way to use the SWAN. You could enter at any point and trace in any direction clockwise or counterclockwise, so long as you proceed along the designated path. This should be fairly straight-forward with one exception: the WSR/PTP chart.

4

Clarification of WSR/PTP Chart

To clarify, the WSR/PTP chart is actually a dual chart with a common line at 1.0. The portion of the graph above the 1.0 line represents WSR and the area below 1.0 is PTP. When moving to this chart from PLS, first enter the WSR portion and then drop down to the PTP portion before reading DE. Moving from PLS to PTP before moving to WSR will give an erroneous DE. For instance, in the above example, if we had moved right from the 0.9 PLS line to the 0.9 PTP line, then up to the 0.9 WSR line, and finally to DE, our DE would have been about 0.84 which is significantly off from the true DE. Thus, it's important to maintain the relationships between "adjacent" parameters.

Representative Applications for the SWAN

As previously mentioned, you can enter SWAN at any point and then proceed in the desired direction. Here are some possibilities.

Example 1 (see Figure 2) - - - Determine the yield needed to achieve a DE of 0.80 against a 2000 psi target using a specific weapon system (fixed PLS, WSR, and PTP at 0.9, 0.9, and 1.0 respectively and CEP fixed at 300 feet). First, draw a vertical line at 300 feet CEP across all yield lines. Then, entering at a DE of 0.80, move left to the 1.0 PTP line, up to the 0.9 WSR line, left to the 0.9 PLS line, up to the 2000 psi line, and right intersecting the 300 feet CEP vertical line. This point of intersection indicates a need of about 200 KT yield.

Figure 2. Example 1

5

Example 2 (see Figure 3) - - - Using a specific weapon
system (50 KT, 200 feet CEP, 1.0 PLS, 0.9 WSR, 1.0 PTP) find
the hardest class of targets that can be attacked and
achieve a 0.75 DE. First, enter at 200 feet CEP; move down
to 50 KT and draw a horizontal line left from this point
of intersection across all lines of hardness. Then enter at
a DE of 0.75 and move left to 1.0 PTP, up to 0.9 WSR, left
to 1.0 PLS, and up intersecting the horizontal line drawn
left from 50KT across all lines of hardness. This point of
intersection indicates targets hardened up to about 7000 psi
could be attacked.
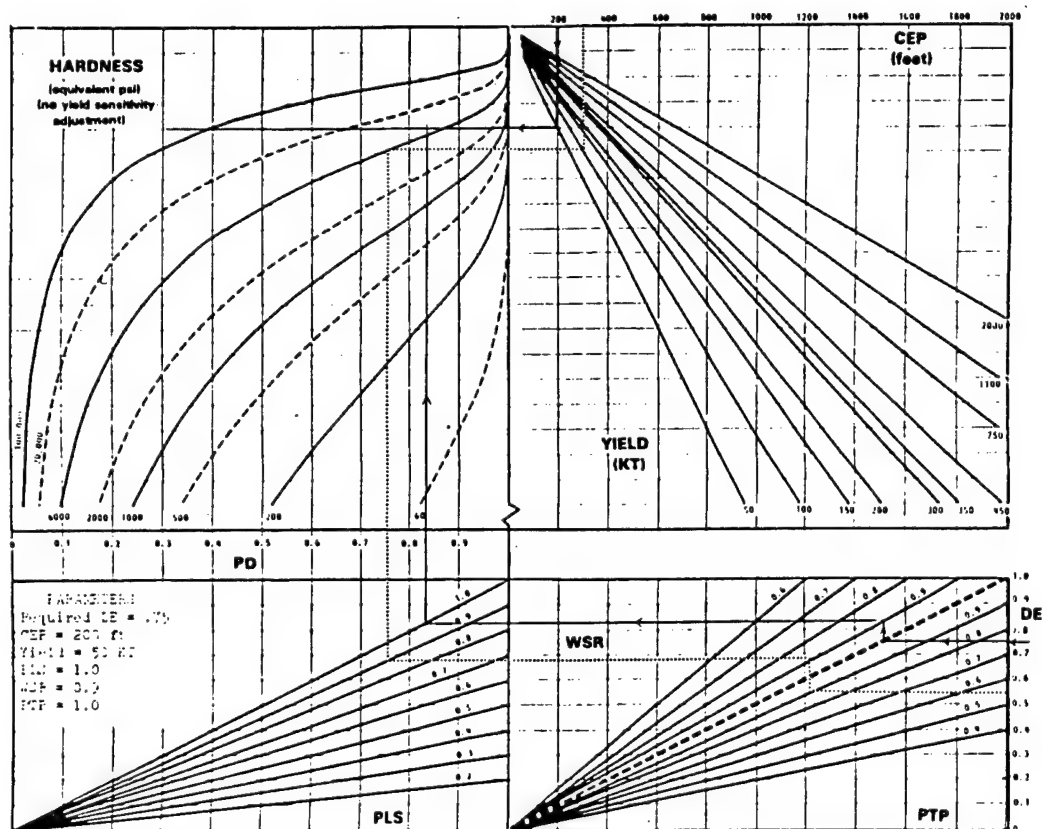
Figure 3.   Example 2

Example 3 (see Figure 4) - - - Find the PLS level needed to achieve a DE of 0.6 against a 500 psi target using a weapon of 150 KT, 400 feet CEP, 0.8 WSR, and 0.9 PTP. First enter at a DE of 0.6; move left to 0.9 PTP, up to 0.8 WSR, and draw a horizontal line from this point across the PLS lines. Next move down from 400 feet CEP to the 150 KT line, left to the 500 psi line and down intersecting the horizontal line, indicating that a PLS of about 0.85 is needed.

Figure 4. Example 3

[A special note concerning DE: As discussed in chapter 1, one additional parameter (C3) is sometimes included in calculating DE. To find the DE using C3, multiply the DE value obtained from the chart by the C3 value. To show this graphically, add one additional chart to the right of the WSR/PTP chart. This additional chart would look exactly like the PLS chart.]

3. SWAN7 - - REVISED VERSION OF SWAN
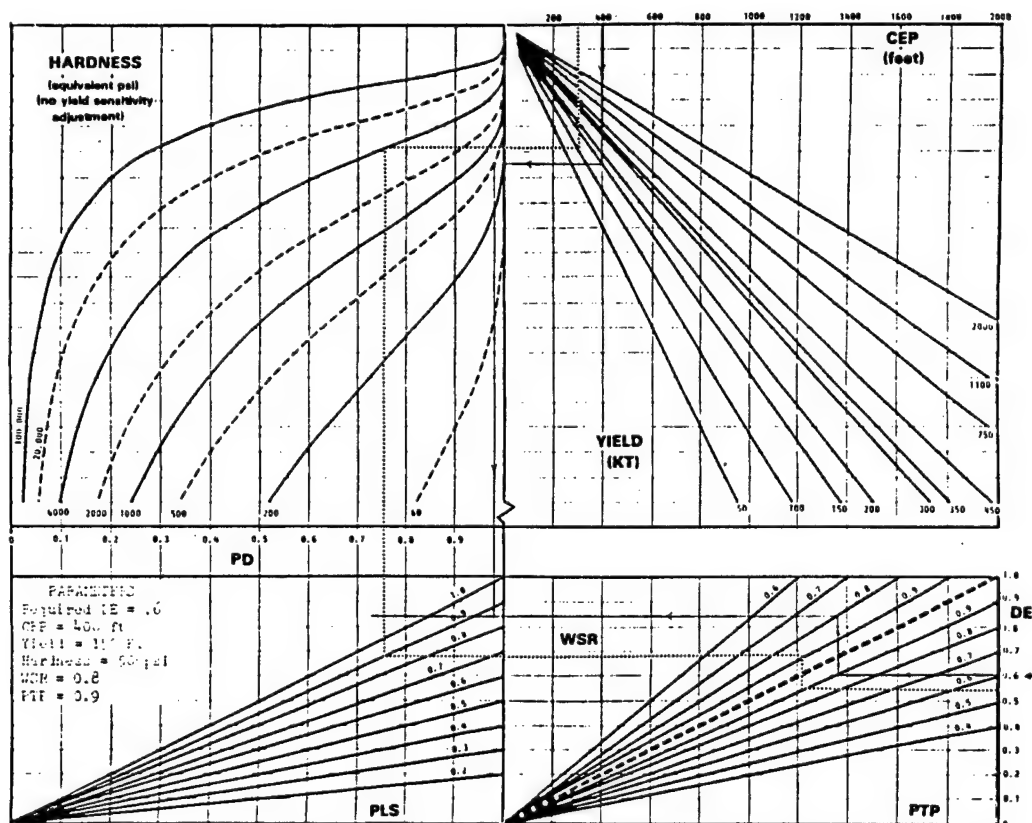
As mentioned in section 1 and Appendix I, one of the major assumptions of the SWAN was a K-factor of zero (i.e., insensitivity of target response to changes in overpressure duration). However, many targets may be very sensitive to pressure duration, with the duration being determined by the yield. In these cases, an equivalent psi level based on the VNTK parameters and the yield must be calculated before entering the model.

Overcoming a SWAN Limitation

The effect of increasing sensitivity can be shown as a shifting of the hardness curves towards a PD of 1. To illustrate this effect, Figure 5 shows that a 100,000 psi hardness for a 20 KT weapon is equivalent to only about 21,300 psi for a 1 MT yield (using a K-factor of 9) due to the longer pulse of the larger yield and the high sensitivity (K = 9) to pulse duration. Thus, as the combination of these parameters changes, one must shift to different equivalent psi curves before determining PD. This conversion process to equivalent psi can be rather cumbersome. To diminish this problem, a new version of the SWAN was necessary.
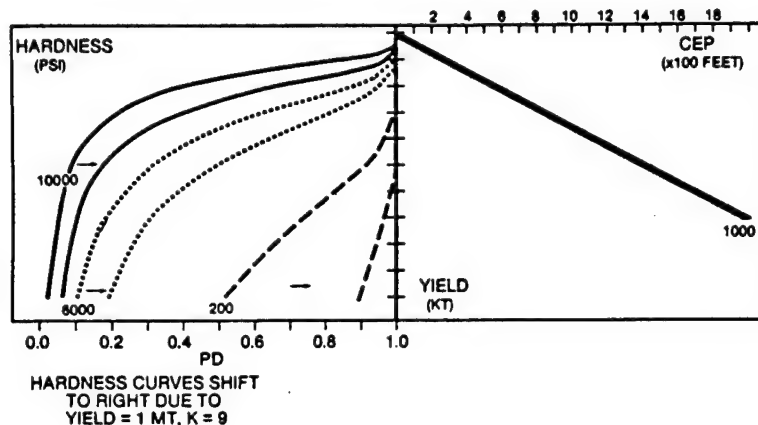

Figure 5. Effect of Non-zero K-factor

SWAN7 Description

This new version of the SWAN, shown in Figure 6, uses a more appropriate K-factor of 7; thus the name SWAN7. The rationale for choosing K = 7 appears in Appendix III under separate cover. Since hardness is a function of yield for a non-zero K-factor, the hardness curves had to be scaled to a specific yield. The yield chosen was 1 MT.

Using a 1 MT yield and a K-factor of 7, the VN numbers were adjusted accordingly so as to obtain the same hardness curves as before. The yield lines were then replotted.
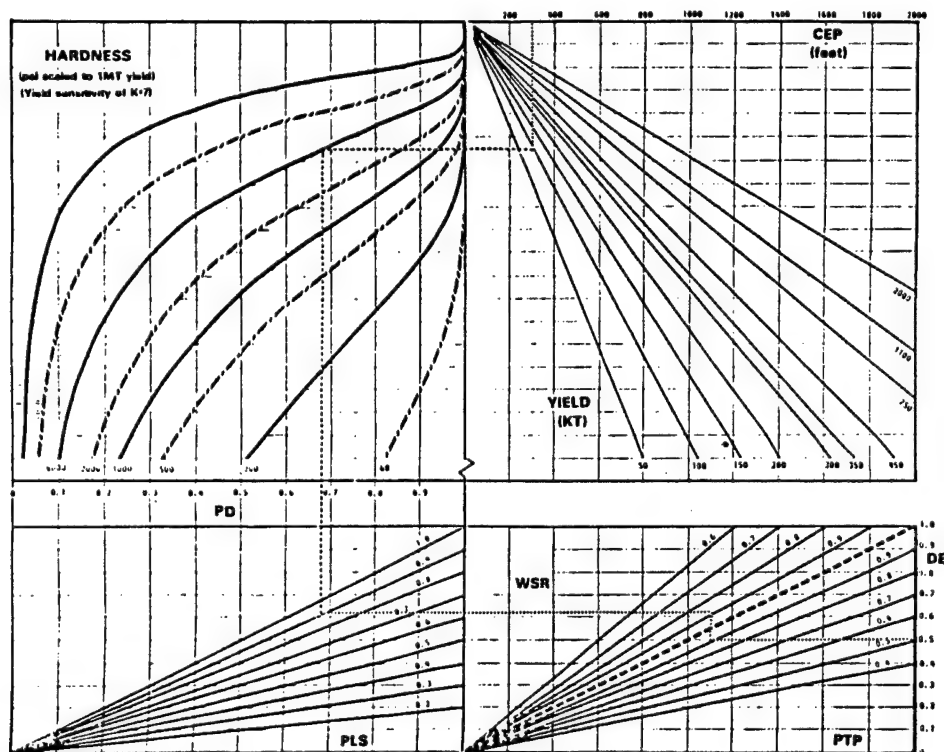
Figure 6.   SWAN7

Interpretting SWAN7

In comparing SWAN7 with SWAN (the K=0 model), one notes a shift of the yield lines away from the 1 MT standard. Thus, for yields less than 1 MT, SWAN7 produces lower values of PD than SWAN. For yields above 1 MT, SWAN7 produces higher values of PD than SWAN. Both models produce the same PD values, if yield equals 1 MT.

From an intuitive standpoint, this shifting indicates that lower yields have shorter pressure durations and thus lower PD values. Conversely, higher yields have longer pressure durations and thus higher PD values. Thus SWAN7 is more responsive to the frequently-encountered non-zero K-factor situation.

9

Figure 7 shows an example of how PD varies due to different K-factors. This variation is most pronounced when operating in the "over the knee" region discussed in section 4 (see Figure 8). As shown, the greatest variations occur for K equal to 6, 7, 8, and 9. Thus a value of 7 was chosen to account for these cases of greatest deviation from SWAN. SWAN is still quite appropriate for small K values.

SWAN HARDNESS LEVEL = 100,000 PSI

Figure 7.   PD Variance due to K-factor

Figure 8.   Hardness Regions: PD Variability due to K-factor

10

Choosing Between SWAN and SWAN7

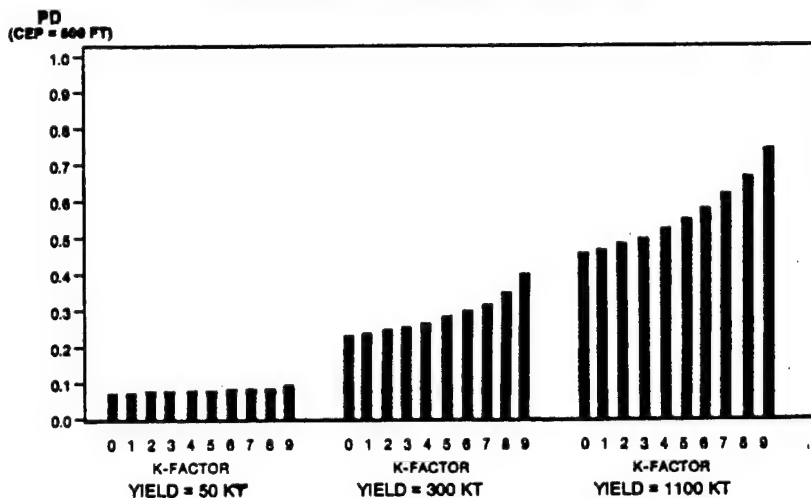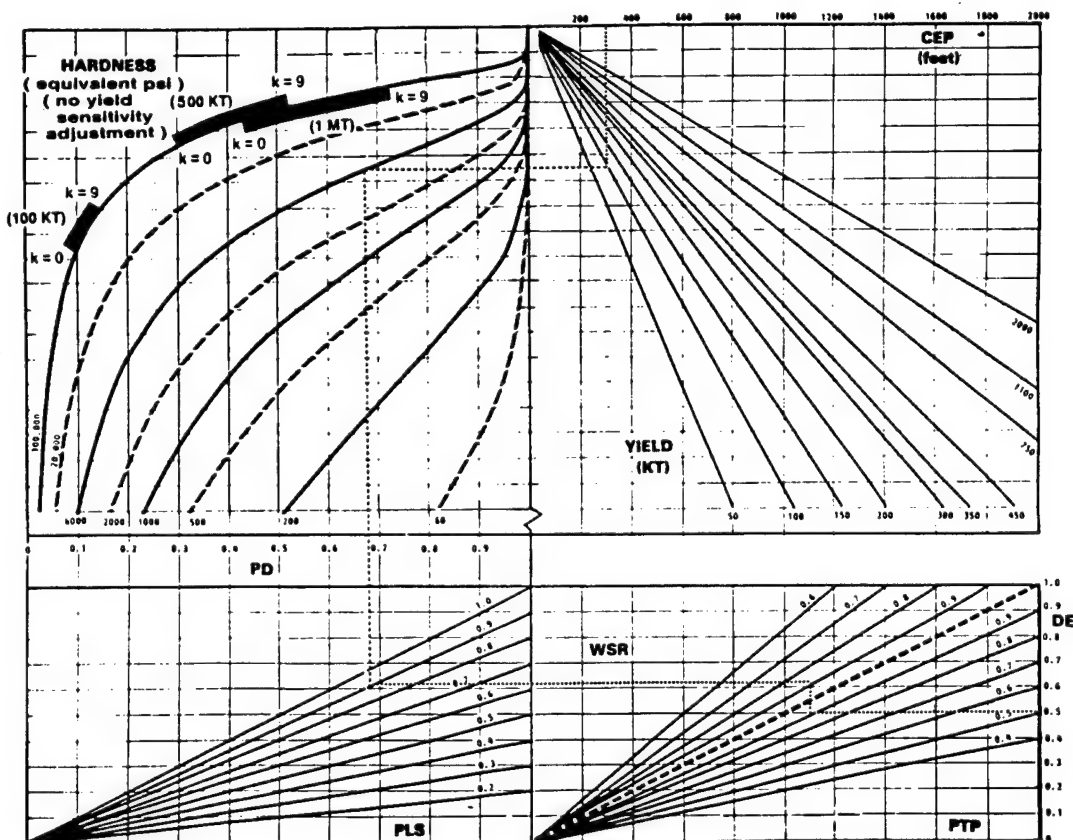The specifics on how to trace through the SWAN nomograph presented in section 2 apply to SWAN and SWAN7. The relationships among the various parameters also are unchanged. Thus, the only difference between SWAN7 and SWAN is the PD and DE values obtained from each. The question then is when to use which version.

Based on target construction characteristics, SWAN7 is probably most appropriate in analyzing weapon systems vis-a-vis harder targets, since it is based on a more representative K-factor of 7. However, SWAN may be preferred for the softer target analysis and in those special cases where targets are less sensitive to yield variations and pressure durations. If one has a specific target in mind (i.e., known K-factor and pressure), then one or both versions could be used to bracket the DE value. Thus, both versions are of use in projecting weapon systems capabilities and have utility in strategic force analyses.

4. MODEL INSIGHTS

There are numerous insights the SWAN offers. In some cases, though the information may be fairly well known, seeing it displayed graphically reenforces the image and could offer greater understanding. In other cases, the insights revealed through the SWAN may not be so obvious. Either way, the SWAN is a useful tool in understanding the relationships among the various DE parameters.

In an effort to show the applicability of this model, I will discuss several varied examples. In each case, I will first present the example and then discuss the insights it offers. For these discussions, I will use SWAN7, realizing that the actual values of PD and DE would be different, if I were to use SWAN instead. However, the general arguments presented here hold true, regardless of whether SWAN or SWAN7 is used.

Note that, since the SWAN is based on DE, it can be viewed as two parts. The upper portion focuses on the target area (PD) and the lower portion focuses on getting the weapon to the target area (PA). Therefore, one could narrow his field of view and concentrate on only half of the model or even a single quadrant, depending on the topic one wishes to investigate. Furthermore, not only could estimates of PD be made using the upper half of SWAN, but estimates of PA could also be made using the lower half, if one assumes PD = 1. For initial discussions, the prime issue will be assessing tradeoffs among the PD parameters. One could apply these discussions to some generic missile system to enhance our understanding of the issues. Then attention will shift to the lower half of the SWAN in assessing tradeoffs among the PA parameters. In this case, a generic bomber system might be more appropriate for discussion purposes.

Insights Concerning Model Convergence

First of all, one could focus on the upper half of the model (i.e., the CEP/yield and the hardness/PD charts) to assess trade-offs among weapon characteristics and target characteristics. This type of comparison is easily done on the SWAN.

Horizontal Lines of Comparison

Looking at Figure 9, we see that the above weapon/target comparison is simply a matter of horizontal moves on the CEP/Yield chart. For example, for a PD of 0.70 on a 6000 psi hardness, one could use 150 KT at 360 feet CEP, or 50 KT at 230 feet, or 750 KT at 660 feet, or any other combination along the 0.70 line in Figure 9. In other words, for a specified PD level and psi level, one can move along a horizontal line to determine numerous combinations of CEP and yield. The SWAN could thus help in force modernization discussions by assessing current force capabilities against various target hardnesses, and by determining the types of improved forces needed in the future to address projected requirements.
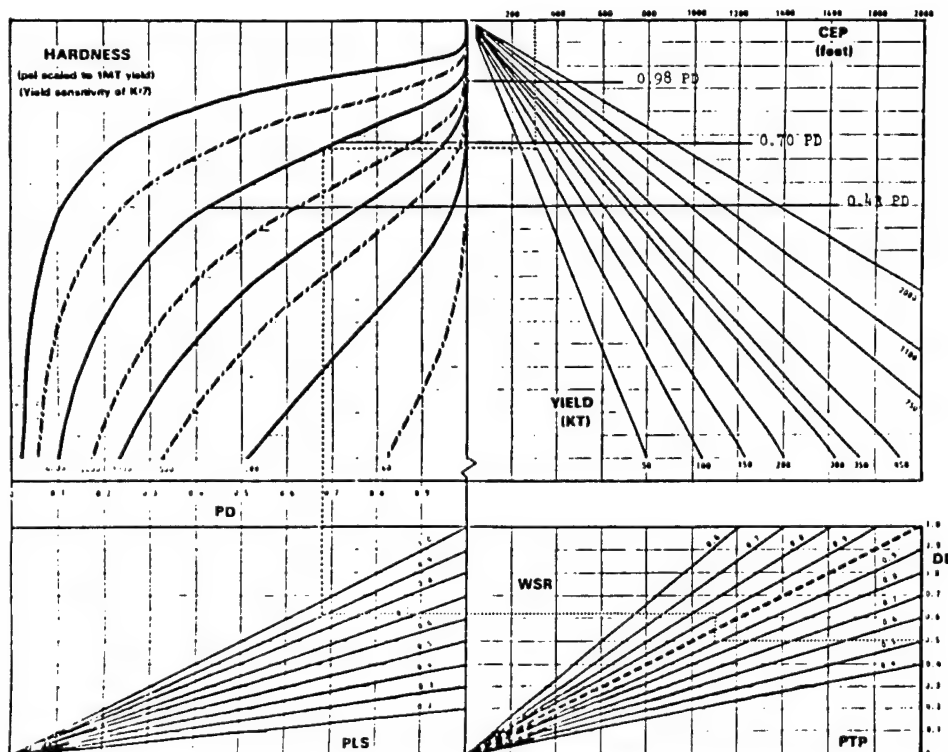

Figure 9. Depicting Horizontal Lines of Comparison

Preference of CEP over Yield

A second observation is that the yield lines converge at CEP = 0 as the psi lines converge at PD = 1. In light of this, consider these parameters for our generic missile:

CEP = 600 ft; Yield = 200 KT; Hardness = 6000 psi; -> PD = 0.43

Lowering CEP,

CEP = 400 ft -> PD = 0.70

Lowering CEP again,

CEP = 200 ft -> PD = 0.98

To attain these same levels of PD with CEP fixed at 600 feet, we need the following increases in yield:

CEP = 600 ft; Yield = 200 KT; Hardness = 6000 psi; -> PD = 0.43
Yield = 450 KT; -> PD = 0.70
Yield = 4050 KT; -> PD = 0.98

Thus, in this situation, lowering the CEP by 400 feet is equivalent to increasing the yield 20 fold! Because of this convergence of yield lines, less and less benefit is gained from yield increases as CEP decreases. In fact, reducing the CEP gains more than increasing the yield by the same percentage. To explain, when reducing CEP, we move upward along a line of constant slope. As shown in Figure 9, for the lower yields, the slope is much steeper, indicating large benefits gained from relatively small improvements in CEP. To obtain comparable improvements in PD through yield increases, the yield would have to increase several fold since we would be moving vertically instead of directly towards convergence (Figure 10).

Given a choice between the two, the CEP improvements may often be preferred since they offer additional benefits such as lower fallout from the smaller yield (which could be important from the standpoint of fratricide and post-attack occupation) and a smaller booster to carry the smaller weapon (offerring options in mobility, basing, etc.). However, one should realize that improvements in CEP often require much more technological effort and money than simply increasing the yield. This is especially true as you approach the convergence region.
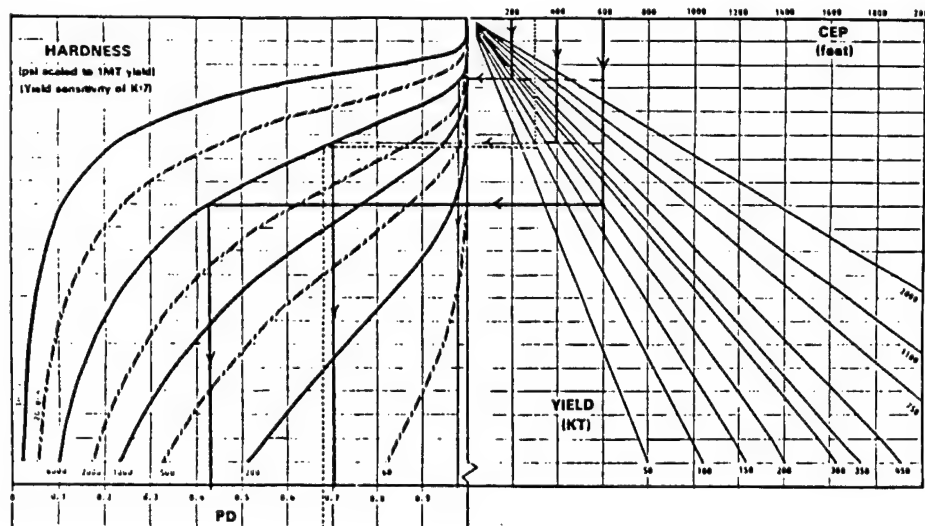
Figure 10. Preference of CEP over Yield in Modernization

<u>Limits</u> <u>to</u> <u>CEP/Yield</u> <u>Improvement</u>
        Now suppose we opted for improving our missile in the
above scenario via the CEP route. The parameters are:

CEP = 200 ft; Yield = 200 KT; Hardness = 6000 psi; -> PD = 0.98.

Increasing the yield to 300 KT gains very little (PD = 1).
If, instead of increasing the yield, we decrease CEP again
(CEP = 100 ft), we still gain very little (PD = 1). Thus, at
some point beyond the knee of a <u>given</u> <u>hardness</u> <u>curve</u>,
weapon improvements do little to increase PD.   **Thus,**
modernization in the realm of CEP and yield combinations
can only take us so far. Once we begin to approach the
points of convergence, decreases in CEP and increases in
yield offer very small benefits in PD.   Therefore, as we
near these convergence points, we must focus more of our
attention on other areas of force modernization (i.e.,
improving PLS, WSR, and PTP) in order to improve DE.

14

<u>Hardness/PD Chart Insights</u>

Turning our attention now to the Hardness/PD chart alone, notice that, as you move to higher psi plots, the curvatures become greater and greater. Figure 11 shows this graphically. I have indicated the "over the knee" region to be from the point where the hardness curve begins to show a nearly-constant minimum slope to the point where the slope begins to rapidly increase. The "diminishing return" region is that area beyond the increasing slope point. What this indicates is that, at higher psi levels, PD improves slowly for lower levels of CEP and yield. **That is, at low CEP/Yield combinations against relatively hard targets, vast improvements in these weapon parameters are needed to make any noticeable improvements in PD.** The goal is to get "over the knee" on the hardness curves. At higher psi levels, PD improves rapidly in this "over the knee" region.
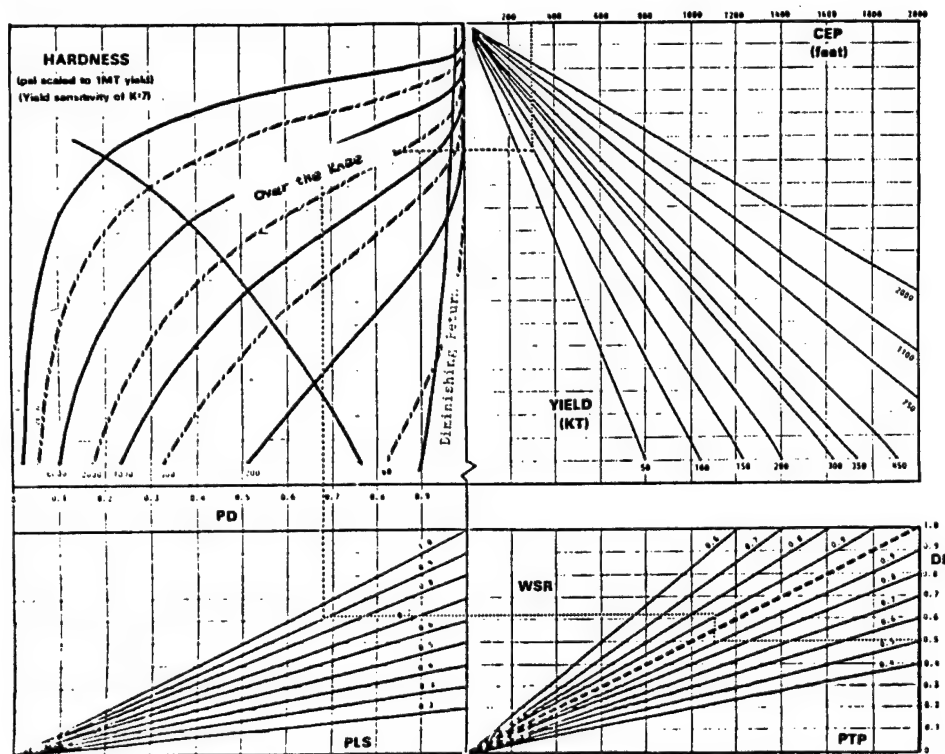
Figure 11. Hardness Regions

It is important to make the distinction between being just "over the knee" and being in the region of "diminishing return." At a point "over the knee," small improvements in CEP/Yield would give large improvements in PD, a fact that offers incentive to make that little extra effort in force modernization. However, at some point, the hardness curve begins to taper off quickly as PD approaches 1. In this "diminishing return" region, weapon improvements do little to increase PD, as discussed earlier. The goal of force modernization should be to at least reach the "over the knee" region and preferably approach the "diminishing return" region for hard-target levels.

15

Hardness Curve Compression

Looking specifically at the logarithmic nature of the PD function, another interesting point is that the hardness curves spectrum compresses as the psi increases (Figure 12). Thus, moving from 0 to 2000 psi lowers PD more significantly than moving from 2000 to 4000 psi. In fact, at relatively large CEPs (e.g., over 1000 ft) moving from 0 to 2000 psi lowers PD more than moving from 2000 to 200,000 psi! This has some important implications.
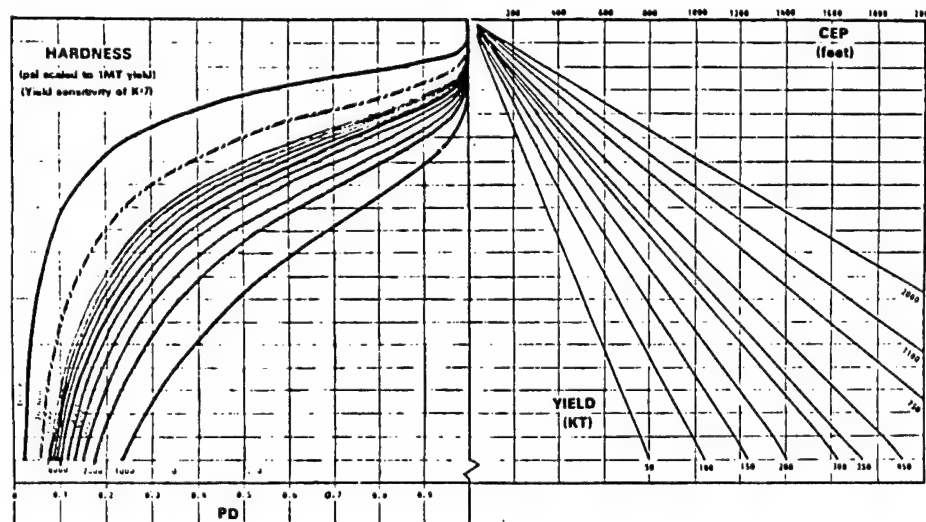
Figure 12. Hardness Curves Compression Effect

First of all, hardening our weapon systems is especially important at the lower end of the spectrum. In particular, moving to the 2000 - 4000 psi range offers impressive benefits. Secondly, moving beyond the 4000 psi level requires increasingly significant improvements in hardness to attain any noticeable decreases in the expected PD against our installations. In other words, moving beyond the 4000 psi level requires significant improvements in hardness to force any noticeable improvements in the CEP or yield of an enemy's weapons. Thirdly, uncertainty in the hardness of a target could have only minimal impact on the CEP/Yield combination needed.

Uncertainty in Hardness
In this latter case, suppose

CEP = 400 ft;   Yield = 200 KT;   Hardness = 6000 psi.

This gives a PD of 0.70. However, if the true hardness is only 4800 psi (i.e., 6000 psi was about 20% overestimated), then PD is 0.73. On the other hand, if the true hardness is about 7200 psi (i.e., 6000 psi was about 20% underestimated), then PD is 0.67. Consequently, for a variation in hardness of +/- 20%, the variation in PD is only about +/- 5%. This holds true regardless of the psi level considered. Taking this one step further, in absolute terms, larger errors at higher psi levels are more acceptable. In other words, 20% of 6000 psi is 1200 psi, but 20% of 200 psi is only 40 psi. Yet both errors have the same impact on PD. Therefore an estimation of a target on the order of 100,000 psi could be off by as much as 20,000 psi and have negligible effect on PD. **This could be of interest in how stringently we establish hardness requirements for our own weapon systems as well as how much effort we need to put forth in refining our estimates of target hardnesses.** However, this is not to say we should relax our goals for future systems, especially since we often need to impose some rather high confidence levels of achieving a specified damage in order to stress technological advances. I'm simply saying that if we don't achieve the specified level because the technology just didn't come through, a 5% deficiency may not be worth worrying about.

PA Insights
Looking now at the PA parameters, each portion is an identical fan chart. Therefore, any discussion concerning one parameter (PLS, WSR, or PTP) would similarly apply to any of the others. Overall, due to the multiplicative nature of PA, any change in one or more of these parameters can have significant effects on DE. For example, consider

PD = 0.9;   PLS = 0.9;   WSR = 0.9;   PTP = 0.9

These produce a DE of 0.66. Thus, though each parameter in itself appears good, the combined effect on DE is rather poor.

As mentioned earlier, as force modernization moves toward convergence on the CEP/Yield chart, we must turn our attention more heavily to the PA parameters. It's apparent that, regardless of how high a PD we can achieve, if PLS, WSR, or PTP are low, DE will fall off sharply. Likewise, low levels in more than one parameter will compound the problem very quickly. This is even more pronounced if one parameter is significantly low, as could be the case with some generic bomber system.

The Need to Focus on PA

Too often the focus in force modernization tends to be on CEP and yield when higher kills are needed. But once the convergence region is reached, as previously discussed, high probabilities of damage are achieved regardless of the target hardness. At this point, PA becomes the primary area of concern. And even if a particular system has not reached convergence, it may still be more advantageous to improve PLS, WSR, and/or PTP at possibly lower costs than to pursue changes in CEP or even in yield.

Realizing that PLS and PTP are functions of policy and strategy as well as the weapon system, it's possible we could improve DE by changes in areas other than weapon characteristics. Consequently this could offer significant dollar savings as well as time savings in implementing such improvements. In a similar fashion, delivery vehicle improvements in system reliability (WSR) and penetrability (PTP) offer strong benefits that may be less costly to implement than extensive technological efforts concerning CEP. Going on the premise that our generic bomber has already reached the convergence region, future improvements in DE may be better attained through policy and strategy than through a high-cost, high-tech force modernization effort.

To realize improvements in PLS, WSR, and PTP, technology, policy, and strategy are not the only avenues to pursue. Understanding the full capabilities and limits of our current systems is also vastly important. The accuracy and sufficiency of operational testing, the accuracy and completeness of maintenance records, the accuracy of enemy defense projections, and the evaluation of operational effectiveness all play an important role in seeking ways to assess DE.

Thus, one must avoid the trap of tunnel vision in viewing weapon system modernization strictly through the confines of CEP and yield. Though improvements in these areas offer higher damage probabilities against harder targets, PD is only one element of the DE function. In addition, as convergence is reached, less benefit is realized from such improvements. Consequently PA is a very important part of DE, especially since PA improvements could be achieved at relatively low costs, and may actually require no weapon system changes at all.

5.   CONCLUSIONS

The SWAN offers some good insights into the relationships among the various damage expectancy parameters. In this respect, it is a valuable tool in educating people on these concepts, whether they be newly assigned analysts to force structuring jobs, managers in need of a better understanding of the DE parameter relationships, or whoever simply wishes to refresh or expand the knowledge in this area.

As a second benefit, the SWAN could be used as a "ballpark" tool in estimating PD and DE for various weapon and target characteristics. Though exact calculations are impossible with such a nomograph, tradeoffs among various weapons and target hardnesses can be easily assessed in relative terms. These comparisons offer strong potential in the areas of force modernization and arms control.

A third area of importance is the general insights in force structuring offerred through the SWAN. By seeing the various DE parameters displayed graphically on one page, the inter-relationships among these parameters reveal some interesting concepts about strategic weapons. For example, the convergence of the yield lines at CEP = 0 as PD approaches 1 indicates that CEP improvements, if technically and economically feasible, gain more in PD than similar degrees of improvement in yield. Furthermore, there is a point at which diminishing returns indicate further modernization in CEP and yield offer little or no utility in improving PD. Beyond this point, efforts should focus more intently on improving the probability of arrival of the weapon (PA). Another insight is that variations in hardness of up to +/- 20% only affect PD by +/- 5%, indicating the bounds of tolerance in estimating enemy target hardnesses and in establishing US hardness levels.

Fourth, the shape of the hardness curves reveals a region over the knees of these curves where weapons should operate, since the greatest benefits in PD are obtained in this region by relatively small improvements in CEP and yield.

Finally, the multiplicative nature of PA indicates that significantly high levels of PLS, WSR, and PTP are needed to ensure a reasonable DE. Seemingly small decreases in these parameters have a rippling effect on lowering DE.

Thus, the SWAN can be a useful little tool in many different areas of interest. Though one must be cautioned not to push the SWAN beyond its limitations, this graphic portrayal of the inter-relationships among the DE parameters has some definite utility.

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APPENDIX I. PD Concepts and SWAN Construction

I.1 PD Mathematics and SWAN Construction Procedures

All calculations made in building the SWAN were obtained from PD SASM Version 2.1. This program uses a lognormal distance damage function in conjuction with the Brode-Speicher generating equations for overpressure vs range to compute P_d. The Brode-Speicher equations are iterated to obtain the range that corresponds to the specified overpressure level. PD is then calculated using the DIA methodology outlined in the DI-550-27-74 mathematical handbook along with the Brode equation value for the r50 distance. The key mathematical formulas used in calculating PD and how these were treated in PD SASM are listed here:

$$PD = \frac{1}{2\pi} \int_0^{2\pi} \int_0^{\infty} P_d(r) \; \frac{1}{\sigma^2} \; e^{-\frac{(r^2 + x^2 - 2rx\cos\theta)}{2\sigma^2}} \; r \; dr \; d\theta \qquad (1)$$

where $P_d(r)$ = distance damage function, which represents the probability that a target will receive at least the specified degree of damage, and is approximated by the complement of the cumulative lognormal function:

$$= -\int_{-\infty}^{z(r)} \frac{1}{\sqrt{2\pi}} \; e^{-\frac{y^2}{2}} \; dy \qquad (2)$$

$C(r)$ = CEP function, which represents the probability that the weapon will land within the specified range, and is approximated by a zero order modified Bessel function of the first kind

$$\doteq \frac{r}{B1} \; B2 \; e^{-\frac{(x-r)^2}{2}} \qquad (3)$$

where B1 and B2 are Bessel variables. If $x = 0$, then $B1 = B2 = 1$.

$$y \;=\; z(r) \;=\; \frac{1}{\beta} \; \ln\left(\frac{WR \; e^{-\beta^2}}{r} \right) \qquad (4)$$

$$WR = \text{weapon radius} = \sqrt{\int_0^{\infty} 2r \; P_d(r) \; dr} = \frac{r_{50}}{1 - \sigma^2} \qquad (5)$$

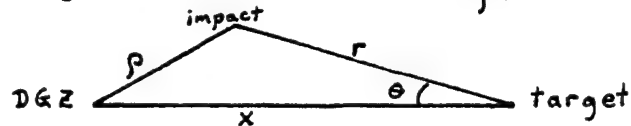= scale parameter of lognormal density function

$$= \sqrt{-\ln(1 - \sigma^2)} \qquad (6)$$

r = distance from ground zero to detonation point

σ^2 = measures variance of the lognormal density function, indicating uncertainty in the probability of damage at or near the weapon radius distance

x = offset distance

Θ = angle of miss distance (ρ) from DGZ, as shown

r50 = ground range from the target at which $P_d(r)=0.5$ for a given target pressure and weapon yield.

In PD SASM, Yield, CEP, HOB, VNTK, and Offset distance are input. The VNTK is converted to equivalent pressure in psi where pressure is a function of the VN, the target type (T-factor), the K-factor, and yield. If an optimal HOB was requested, then HOB is calculated by using a 7th order polynomial approximation fit to the calculated pressure curve.

With these initial calculations, a bisection technique is used to iterate the Brode-Speicher equations to find r50. This r50 value then gives the weapon radius (WR) since it is assumed that the distance-damage function is approximated by the complement of the cumulative lognormal function.

Finally, PD is calculated using a 10-point Gauss-Legendre function of the form

$$PD = \frac{b-a}{2} \sum_{i=1}^{10} W_i \ f\left(\frac{(b-a)z_i + b + a}{2}\right) \tag{7}$$

where

$$f\left(\frac{(b-a)z_i + b + a}{2}\right) = P_d(r_i) \cdot C(r_i) \tag{8}$$

$$r_i = \frac{(b-a)z_i + b + a}{2} \tag{9}$$

$$P_d(r) = 0.5 + 0.5\frac{|z|}{z} \, \mathrm{erf}\frac{|z|}{\sqrt{2}} \tag{10}$$

$\mathrm{erf}\dfrac{|z|}{\sqrt{2}}$ = the error function for the lognormal, given by a numerical approximation equation.

The "a" and "b" parameters and the weapon radius are weighted by the weapon's CEP in the above calculations.

[NOTE: Since the construction of the Strategic Weapons Assessment Nomograph, PD SASM has been replaced by a package called DDF which changes the method of calculating PD. Under DDF, the actual distance-damage function is built instead of using r50 to calculate WR and thus $P_d(r)$. Otherwise PD SASM and DDF operate the same and both produce PD values that are equal to at least two decimal places.]

A detailed description of these functions appears inDI-550-27-74, "Mathematical Background and Programming Aids for the Physical Vulnerability System for Nuclear Weapons."

To build the CEP/Yield plots and the Hardness curves using the data generated from PD SASM:

a. I arbitrarily chose 50 KT as the baseline curve.

b. I chose an arbitrary line and slope for the CEP and Yield plot, based on an initial review of PD SASM calculations, to get a reasonable spread of the scales to enhance readability.

c. With the 50 KT curve established, I plotted data values of PD at each psi level. The VNTK system was used to obtain desired equivalent psi levels, with the following relationships found:

psi	VNTK	
60	21.83	p 0
200	28.43	p 0
500	33.457	p 0
1000	37.26	p 0
2000	41.06	p 0
6000	47.086	p 0
20000	53.69	p 0
100000	62.517	p 0

Note that the VNTK numbers are purely arbitrary for the purpose of building the model. My goal was to plot the exact psi numbers shown here. To obtain these numbers, I could have used numerous VN and K combinations. I simply chose to fix K at "0" for ease in finding the psi levels. To better understand target hardness and the VNTK system, I urge you to read section I.2 of this Appendix.

d. I connected the data points, extrapolating between points to obtain smooth curves for all psi levels, since the PD function is continuous and monotonically increasing. Figure I.1.1 shows the PD function for different hardness levels. Note that the PD function monotonically increases from 0 to 1 as CEP decreases and yield increases. This is true regardless of the psi level. Thus, though the shape parameter of the curve varies with psi, it still converges at a PD of 0 and 1. The cutoff line shown in Figure I.1 indicates the portion of these curves that appears in the upper left quadrant of the SWAN.

e. I calculated two data points (PD for 200 feet CEP/500 psi and PD for 1000 feet CEP/500 psi) for each level of yield and, noting that all yield lines intersect at 0 feet CEP (per DIA methodology), drew the yield lines.
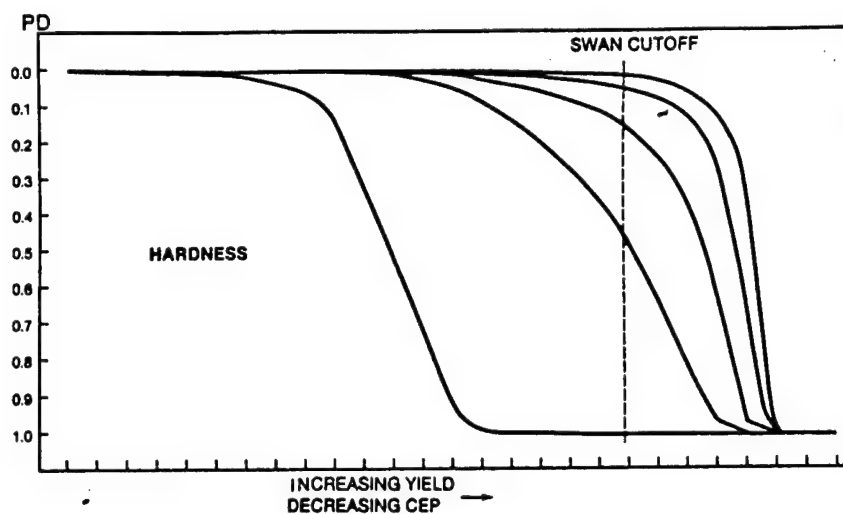
Figure I.1. Showing Convergence and Shape Variability
of Hardness Curves

f. I validated the plots by using 60 arbitrary
combinations of yield, CEP, and psi to obtain PD, comparing
the values I found from the plots with PD SASM calculated
values.

g. SWAN7 was constructed in the same manner as
described above except that the K-factor was fixed at 7, a
standard yield of 1 MT was used, and new VN numbers were
determined to achieve the same psi levels as before. I then
replotted the yield lines based on new calculations of PD
under these revised constraints. Data were obtained at each
psi level for each yield, resulting in a slight adjustment
in the hardness curves at 6000 psi and below. The VNTKs
used for SWAN7 were:

psi	VNTK		
60	26.54	p	7
200	33.14	p	7
500	38.17	p	7
1000	41.97	p	7
2000	45.77	p	7
6000	51.796	p	7
20000	58.399	p	7
100000	67.226	p	7

I.2. PD Constraints - - Understanding VNTK

The SWAN is based on numerous assumptions that were discussed earlier. Using it as a force structuring tool must be done carefully to avoid reaching potentially misleading conclusions. The largest area of concern is the upper half of the SWAN, particularly, the use of the VNTK system.

Defining Target Hardness

Probability of damage depends upon the structural strength of various materials, target construction techniques, and the physics of thermonuclear energy release from a weapon. Understanding the hardness curves on the SWAN involves two issues: calculating the effective hardness levels plotted and determining which curve is appropriate for a specific target.

The hardness curves on the SWAN are plotted to display probabilities of yield/CEP combinations generating various overpressures against single targets. Mathematical formulas (presented in section I.1) approved by DNA are used to plot these curves. These formulas are based on empirical test data gathered since the mid-1940s as well as laboratory research and physics theory. Though the form of these expressions is well defined, the actual values of coefficients within them are less certain (especially for hardnesses above 2000 psi) and have been adjusted numerous times over the years as the empirical database has expanded. Therefore, due to their empirical basis, most points on any of the nuclear hardness curves are subject to the uncertainties associated with scaling weapon yield-to-effect data and mathematical "best fit" methodology.

When using the SWAN in regards to a specific target, the target's hardness is related to the effective overpressure curves to assess the probability of damage. The target's hardness indicates the point at which the target incurs some specified level of damage and is subject to uncertainty in the intelligence reports on the target's construction and in material response to nuclear effects. The empirical basis for hardness assessment is data from Hiroshima and Nagasaki, and nuclear and high-explosive test data. Actul target hardnesses are approved and released by DIA.

If the information about a target gives its equivalent psi rating, this number can simply be applied to the nomograph. However, if the information is given in the form of a VNTK number, then it must be converted into an equivalent psi rating before it can be applied to the nomograph. There are numerous computer packages available that can make this conversion. However, some understanding of the VNTK system may be helpful not only in understanding how VNTK is related to psi, but also in understanding some of the key concepts, assumptions, and limitations of the SWAN.

VNTK Concepts

The VN system is a technique for representing a target's susceptibility to blast damage. When a nuclear weapon explodes, it forms a blast wave composed of two effects: overpressure and dynamic pressure. Though both may act upon a target in some fashion, one usually dominates in causing damage.

To represent a target's susceptibility to blast effects, the VN system uses a three-part alphanumeric setup. The first is the vulnerability number (VN) which reflects the relative hardness of the target in terms of a 20 KT weapon. It uses an arbitrary numerical scale, associating damage probabilities with pressure levels based on a 20 KT yield. The higher the pressure needed to cause a specified level of damage, the higher the VN.

The second part is the T-factor. Various letters are used here to indicate which type of pressure the target is most sensitive to. Each type is further broken down into relative uncertainty levels (sigma) for that pressure. In other words, "T" represents the confidence that a given amount of pressure will cause the desired level of damage. As sigma increases, confidence decreases and the probability of incurring the specified damage drops off inside the weapon radius distance. These sigma levels are a measure of variance in the lognormal density function presented in the mathematics of section I.1, and are designated as follows:

Pressure Type	T-factor	Sigma
overpressure	L	10
	M	30
	N	40
	O	50
	P	20
dynamic pressure	Q	30
	R	10
	S	20
	T	40
	U	50

Finally, the K-factor is an adjustment to the VN due to yield departures from the 20 KT standard. Thus, if a particular yield is expected to cause the same general effects as a 20 KT weapon, as far as blast wave duration is concerned, then K is set to zero. This is frequently not the case in practice, though. Instead, K is often set to a number between 1 and 9, with 9 being the largest adjustment and thus increasing PD the most.

This type of adjustment is necessary because the pressure required to damage a target changes as a function of yield, since the damaging pressure applied to a target acts for a certain duration. In general, the longer a force acts on a target, the lower the pressure needed to cause a specified level of damage. The K-factor adjustment assigned to a target represents a pressure level as well as the duration associated with the pressure level generated by a 20 KT weapon. Larger yields have longer pressure durations. As an example, take a target of

$$VN = 47.086$$
$$T = P$$
$$K = 2$$

for a 20 KT weapon. This gives an equivalent psi of 6000. For a 1 MT weapon, we have

$$VN = 47.977$$
$$T = P$$
$$K = 2$$

This combination gives the same 6000 psi level. In fact, any number of possible combinations of VN, K, and yield could produce the same psi level. The larger the K and yield, the larger the VN. Yet all could equate to the same psi level. For example, the following combinations of VN, K, and yield give the same equivalent 6000 psi rating:

VN	K	Yield
47.086	0	any
48.635	5	100 KT
49.836	5	1 MT
51.4	9	100 KT

The K-factor: Effect of Yield on VNTK
The yield does not affect the VN number when K=0. However, for K not equal to 0, as yield changes, the VN number must change in order to produce the same equivalent psi level needed for building the SWAN. Thus, for different K-factors, we could shift the yield lines according to the target hardness, thereby indicating greater PD values at greater K-factors for the same CEP and yield. Figure I.2 shows the variations in three of the yield lines as K ranges from 0 to 9, using a 1000 psi hardness. The effect of the K-factor is less prominent for greater hardnesses but still shows considerable variation in the yield lines. This figure would map to the same hardness curves appearing in the SWAN. However, the equivalent psi levels would be less for each successively larger K-factor. In essence, these yield lines would map to the hardness curves as though the hardness curves were actually fixed VN curves. In order to determine how different weapons compare in regards to a specific target (i.e., fixed VNTK), the variations depicted in this figure would be essential if K is not zero.
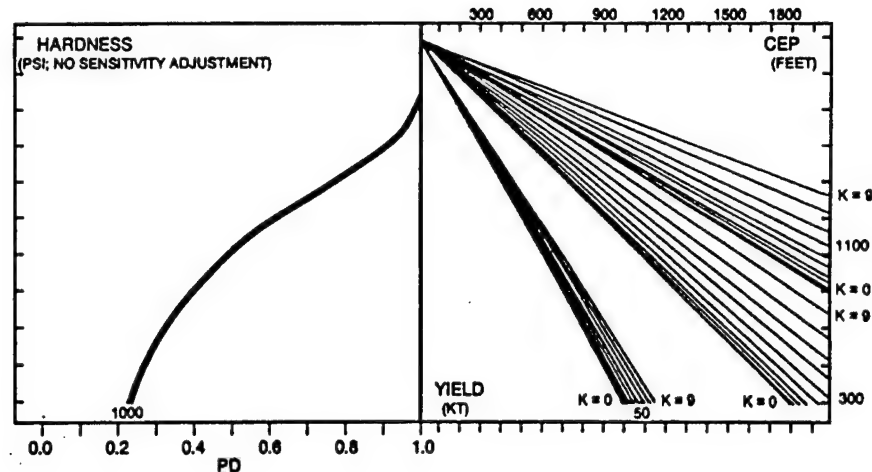
Figure I.2.   Variability Due to K-factor
(1000 psi hardness)

It is important to note that simply stating a target's
hardness in terms of psi is not enough if you are interested
in rigidly defining the target. However, if the goal is to
simply compare weapon capabilites regardless of any
particular target, then the psi level is arbitrary. By
contrast, to use the SWAN for specific target analysis, one
must calculate the equivalent psi overpressure level using
the VN, K, and yield value of interest. To compare two
weapons' abilities against the same target, this calculation
must be made for each weapon. This conversion effort to
equivalent psi makes the use of SWAN a bit cumbersome in
calculating PD, though the general concepts discussed in
Chapter 4 still apply. In an effort to alleviate this
problem, a variation of the SWAN was built. This variation,
called SWAN7 because of the constraint of K=7 instead of
K=0, was discussed in section 3.

Once equivalent psi levels were obtained, the VNTK
system was no longer a major concern for the model's
construction. It is true that, for different yields,
changing the K factor would result in different PD values.
However, in so doing, you would also have a different
equivalent psi level and thus you would map to a different
psi curve. The point is that the psi curves are, more
specifically, equivalent static overpressures.

I.8

The T-factor: Effect of Target Uncertainty on SWAN

        As for the type of target (T) chosen, I selected "P"
(i.e., sigma of 0.2) simply as a common middle-of-the-road
value used in most literature.   However I performed some
sensitivity analysis, varying the T-factor, to determine how
significantly PD might change as the target sigma changes.
Plots of these curves appear in Figures I.3, I.4, and I.5
for psi levels of 60, 2000, and 6000, respectively.   Note
the crossover of the curves in Figures I.4 and I.5.   To the
right of this point, as sigma increases, PD decreases.
Also, these points converge again at PD=1 as CEP approaches
0.   These same arguments hold true for Figure I.3 though all
that is shown in this figure is the upper portion of the 60
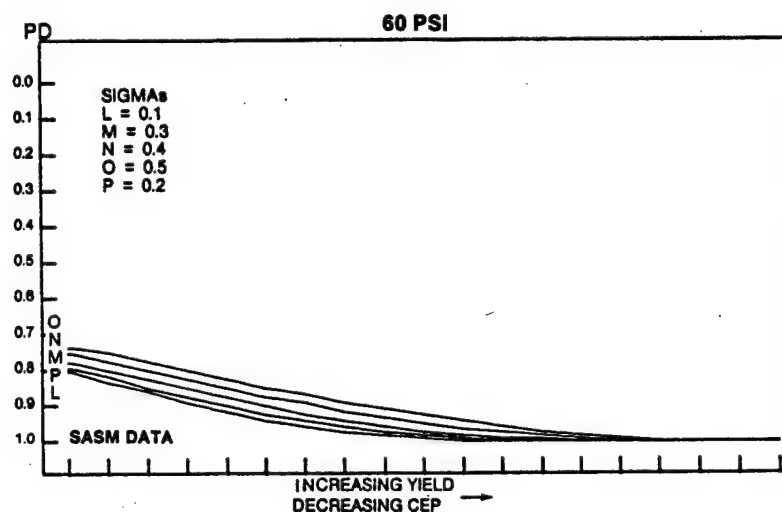psi plots above the crossover point.

Figure I.3.   Hardness Curve Variance Due to T-factor
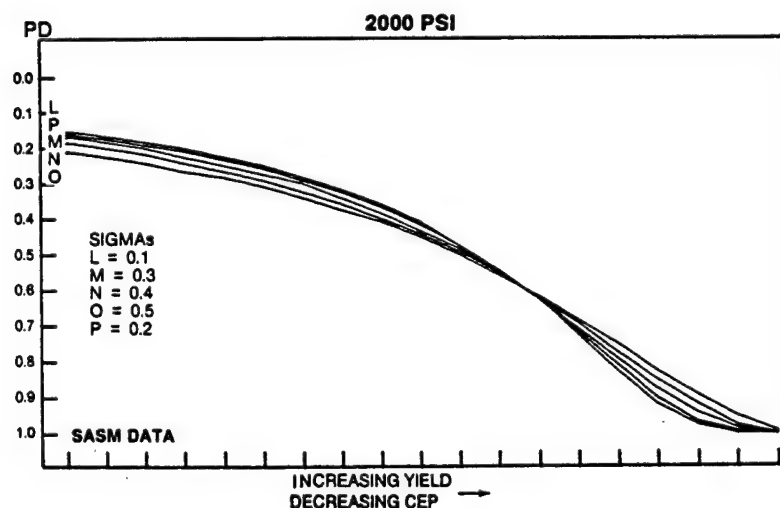   (60 psi – PD SASM data)

Figure I.4.   Hardness Curve Variance Due to T-factor
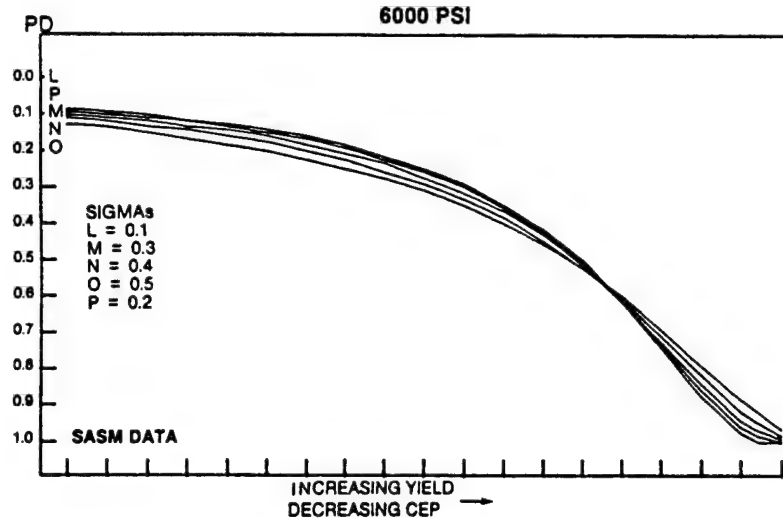   (2000 psi – PD SASM data)

Figure I.5. Hardness Curve Variance due to T-factor
(6000 psi — PD SASM data)

     Note that the maximum spread of these curves indicates
that the projected PD value found on the SWAN (using a0.2
sigma) could be as much as about 0.1 too high (worst case)
if the sigma were to change to 0.5. Unfortunately, this
maximum spread happens to occur as one enters the
convergence region of CEP and Yield. The consequence is
that a particular force modernization effort may not gain as
much as expected. For example, suppose such an effort moves
you to a CEP of 200 feet and a Yield of 100 KT. Further
suppose this new weapon is to be used againsta 6000psi
hardness. The SWAN (using a 0.2 sigma) projects a0.95 PD
value. However if one uses a sigma of 0.5, the projected PD
would only be about 0.87. The question of how significant
this consequence is depends on the decisionmaker's needs.
Note that the SWAN will project PD values on the high side
when PD is above about 0.5 since a sigma of0.2 produces
higher PD values in this upper region.
     Another point of interest is the convergence to PD=1
for these T-factor curves, as previously mentioned. This is
a built-in assumption of the PD calculations in PD SASM.
That is, based on the DIA guidelines outlined in AP-550-1-2-
INT, PD SASM calculates the PD value by allowing the weapon
radius to vary with the sigma value. Consequently, as sigma
(the uncertainty of the target's response) increases, the
weapon radius increases in order to maintain the 50% damage
circle about the ground zero point. By including the change
in sigma in the PD calculations as well as adjusting the
weapon radius as discussed, these two parameters tend to
offset one another in such a way as to cause PD to converge
to one as CEP approaches zero for all sigma. This is true
even if sigma is 0.99! This concept is an inherent feature
of the lognormal function which is used by DIA and in PD
SASM.

I.3.   PD Constraints -- Zero Offset

In addition to the VNTK constraints discussed above, the
assumption of zero offset targeting placed a further constraint
on the SWAN. To understand this constraint, we begin by referring
to   Figure I.6.   This figure is a plot of yield   lines
corresponding to the 6000 psi hardness curve with an offset equal
to 500 feet. Note that at CEP = 500, the lines begin to diverge.
In fact, for the lower yields, at some point, the yield lines
bend downward.   This indicates that, as accuracy approaches
perfection, a certain yield will have less and less effect on the
target since it becomes "more certain" of falling outside the
vulnerability range of the target. However, as CEP increases, a
small   probability that the weapon would fall inside   the
vulnerability range begins to arise (i.e., it will miss the
offset aim point and actually detonate closer to the target than
it was supposed to). Thus, the curve moves upward, corresponding
to a higher PD on the SWAN.   The yield soon begins to fall off
again as we move beyond this special region due to greater
inaccuracies.
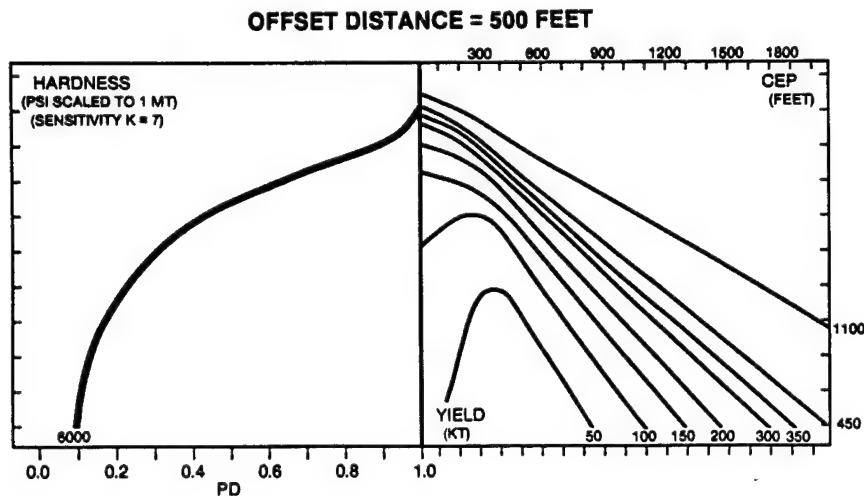
Figure I.6.   CEP/Yield Line Variability Due to Offset
(500 feet offset, 6000 psi hardness)

Note that this region is less evident for higher yields since the effective radius of these larger yields extends beyond the offset distance so that the weapon always overlaps the vulnerability range of the target. If we look at lower target hardnesses or lower offsets, we see that the effect of offset is less noteworthy here, as well. For example, Figure I.7 shows the same yield lines as before but for a 200 psi hardness. In this case, the yields tend towards convergence as in the SWAN. One final point about these figures is that all of these yield lines fall below their counterparts on the SWAN. Thus, an offset of zero (the SWAN) is the best-case situation. For non-zero offsets, the actual PD would always be less than the PD found on the SWAN.
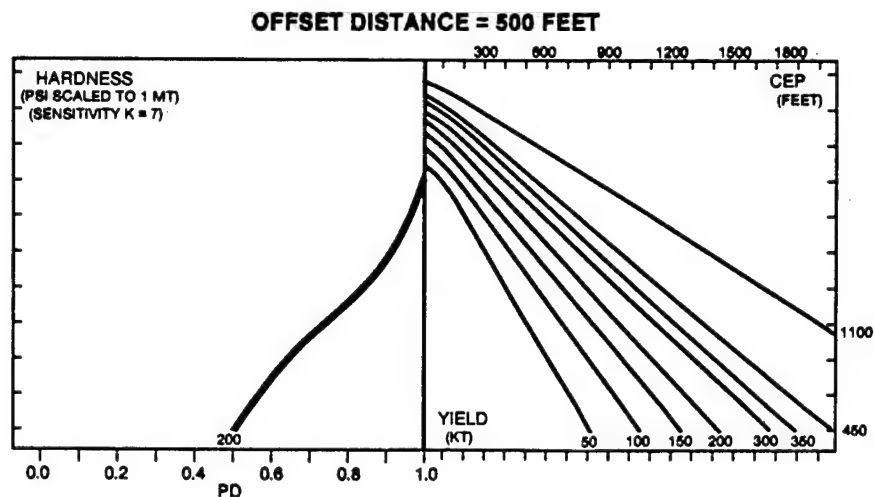

Figure I.7.   CEP/Yield Line Variability Due to Offset
             (500 feet offset, 200 psi hardness)

In light of this important issue, there appears to be a point at which yield increases are preferred over CEP increases for some target hardnesses when the offset is not zero. This is contrary to the previous discussions for the zero offset case (i.e., the SWAN). Looking at Figure I.9 again, note that improvements in CEP for a 50 KT weapon are actually detrimental to PD once CEP reaches about 400 feet. Therefore, for non-zero offsets, instead of decreasing the CEP below this cutoff point, the yield should be increased. For larger yields, the cutoff point is less apparent, if at all. Also, the divergence of the yield lines is less prominent for lower values of offset and lower hardnesses. Thus, for small offsets and low hardnesses, the previous discussion still holds (i.e., prefer CEP improvements over Yield increases and there is some point at which neither gains much). However, for larger offsets and hardnesses, the opposite would be true and a point of convergence may never be attained. In this latter case, we would strive for high accuracy and large yields. The bottom line is that one must be careful of how he applies the SWAN, if he hopes to obtain meaningful information from it.

Note that this region is less evident for higher yields since the effective radius of these larger yields extends beyond the offset distance so that the weapon always overlaps the vulnerability range of the target. If we look at lower target hardnesses or lower offsets, we see that the effect of offset is less noteworthy here, as well. For example, Figure I.10 shows the same yield lines as before but for a 200 psi hardness. In this case, the yields tend towards convergence as in the SWAN. One final point about these figures is that all of these yield lines fall below their counterparts on the SWAN. Thus, an offset of zero (the SWAN) is the best-case situation. For non-zero offsets, the actual PD would always be less than the PD found on the SWAN.
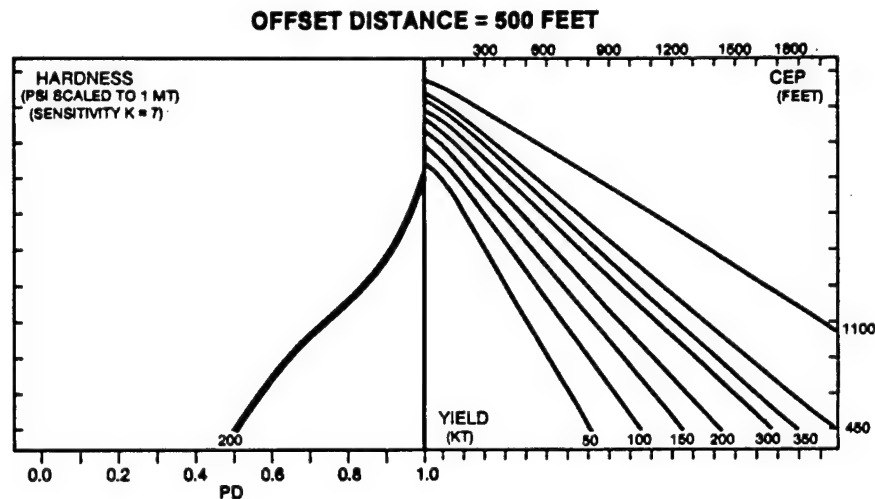
OFFSET DISTANCE = 500 FEET

Figure I.10.   CEP/Yield Line Variability Due to Offset
(500 feet offset, 200 psi hardness)

In light of this important issue, there appears to be a point at which yield increases are preferred over CEP increases for some target hardnesses when the offset is not zero. This is contrary to the previous discussions for the zero offset case (i.e., the SWAN). Looking at Figure I.9 again, note that improvements in CEP for a 50 KT weapon are actually detrimental to PD once CEP reaches about 400 feet. Therefore, for non-zero offsets, instead of decreasing the CEP below this cutoff point, the yield should be increased. For larger yields, the cutoff point is less apparent, if at all. Also, the divergence of the yield lines is less prominent for lower values of offset and lower hardnesses. Thus, for small offsets and low hardnesses, the previous discussion still holds (i.e., prefer CEP improvements over Yield increases and there is some point at which neither gains much). However, for larger offsets and hardnesses, the opposite would be true and a point of convergence may never be attained. In this latter case, we would strive for high accuracy and large yields. The bottom line is that one must be careful of how he applies the SWAN, if he hopes to obtain meaningful information from it.

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GLOSSARY

C3	Command, Control, and Communication
CEP	Circular Error Probable
DDF	Distance Damage Function
DE	Damage Expectancy
DIA	Defense Intelligence Agency
HOB	Height of Burst
KT	Kiloton
PA	Probability of Arrival
PD	Probability of Damage
PLS	Pre-launch Survivability
psi	pounds per square inch
PTP	Probability to Penetrate
SICBM	Small ICBM
SWAN	Strategic Weapons Assessment Nomograph
WSR	Weapon System Reliability

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